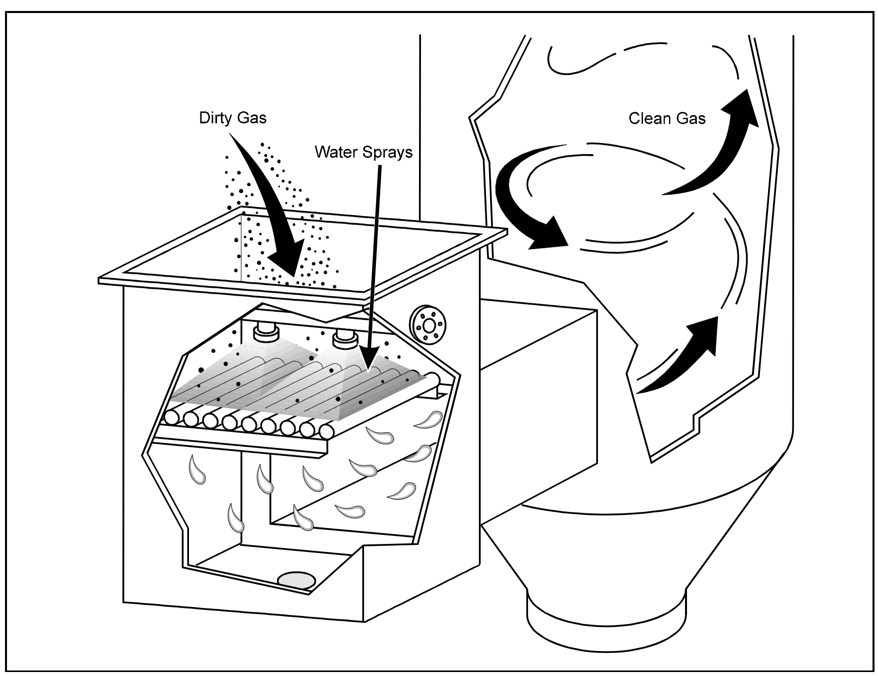
Environmental
Programs

Scrubber Systems Operation Review

Self-Instructional Manual

APTI Course SI:412C
Second Edition



Industrial Extension Service   College of Engineering   North Carolina State University

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Scrubber Systems Operation Review

Self-Instructional Manual

APTI Course SI:412C
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Notation

English Symbols

Symbol		Definition
A	-	Cross-sectional area of Column A
a	-	Interfacial contact area
B	-	Parameter characterizing the liquid-to-gas ratio
C_D	-	Drag coefficient for the liquid at the throat entrance
C_c	-	Cunningham slip correction factor
c_A^*	-	Equilibrium concentration of solute A at operating conditions
c_{AI}	-	Concentration of solute A at the interface
c_{AL}	-	Concentration of solute A in the liquid
d_d	-	Droplet diameter
d_p	-	Particle aerodynamic resistance diameter
d_{pg}	-	Particle aerodynamic geometric mean diameter
d_{ps}	-	Particle physical, or Stokes, diameter
d_t	-	Diameter of column
F	-	Packing factor
f	-	The percent of flooding velocity
G'	-	Gas mass flow rate per cross-sectional area of tower
G_m	-	Gas molar flow rate
g_c	-	Gravitational constant
H	-	Henry’s law constant, Pa/mole fraction
H'	-	Henry’s law constant, mole fraction in vapor per mole fraction of liquid
H_{OG}	-	Height of a transfer unit based on an overall gas-film coefficient, m
H_{OL}	-	Height of a transfer unit based on an overall liquid-film coefficient, m
HTU	-	Height of a transfer unit

K_{OG}	-	Overall mass-transfer coefficient based on gas phase
K_{OL}	-	Overall mass-transfer coefficient based on liquid phase
K_{po}	-	Inertial parameter at venturi throat entrance
K_{pg}	-	Inertial parameter for mass-median diameter
k_g	-	Mass-transfer coefficient for gas film (two-film theory)
k_l	-	Mass-transfer coefficient for liquid film (two-film theory)
L_m	-	Liquid molar flow rate
L/G	-	Liquid-to-gas ratio
L_m/G_m	-	Liquid-to-gas ratio (mass flow rates)
ℓ	-	Venturi throat length parameter, dimensionless
ℓ_t	-	Venturi throat length
m	-	Henry's law constant for the equilibrium diagram
N_A	-	Rate of transfer of component A (two-film theory)
N_{OG}	-	Number of transfer units based on an overall gas-film coefficient, K_{OG}
N_{OL}	-	Number of transfer units based on an overall liquid-film coefficient, K_{OL}
N_p	-	Number of theoretical plates
N_{Reo}	-	Reynolds Number
N_t	-	Number of transfer units (plate towers)
NTU	-	Number of transfer units
P	-	Pressure
P_G	-	Power input from gas stream
P_L	-	Power input from liquid injection
P_T	-	Total contacting power
Pt	-	Penetration
p	-	Partial pressure of solute at equilibrium
p_A^*	-	Equilibrium partial pressure of solute A at operating conditions
p_{AG}	-	Partial pressure of solute A in the gas
p_{AI}	-	Partial pressure of solute A at the interface
p_L	-	Liquid-inlet pressure
Q_G	-	Gas flow rate
Q_L	-	Liquid flow rate
R	-	Ideal gas constant
T	-	Temperature

T_g	-	Gas temperature
T_l	-	Water temperature
v_{gt}	-	Gas velocity in the venturi throat
X	-	Mole fraction of solute in pure liquid
Y	-	Mole fraction of solute in inert gas
Z	-	Height of packing

Greek Symbols

Symbol		Definition
α	-	Empirical constant used in contact power theory
β	-	Empirical constant used in contact power theory
Δp	-	Pressure drop
ϕ	-	Ratio of specific gravity of scrubbing liquid to that of water
η	-	Collection efficiency
ψ	-	Empirical correlation used to size a plate tower
μ_g	-	Gas viscosity
μ_l	-	Liquid viscosity
ν_g	-	Gas kinematic viscosity
π	-	Pi, value = 3.14
ρ_g	-	Gas density
ρ_l	-	Liquid density
ρ_p	-	Particle density
σ_{gm}	-	Geometric standard deviation

Units of Measurement

Abbreviation		Unit of Measurement
acfm	-	Actual cubic feet per minute
cfm	-	Cubic feet per minute
cm	-	Centimeter
ft	-	Foot

g	-	Gram
gal	-	Gallon
g-mol	-	Gram mole
h	-	Hour (metric)
hp	-	Horse power
hr	-	Hour (English)
in.	-	Inch
kg	-	Kilogram
kPa	-	Kilopascal
L	-	Liter
lb	-	Pound
lb-mole	-	Pound mole
MW	-	Megawatt
m	-	Meter
min	-	Minute
mm	-	Millimeter
mol	-	Mole
mph	-	Miles per hour
Pa	-	Pascal
ppm	-	Parts per million
psi	-	Pounds per square inch
psig	-	Pounds per square inch (gauge)
s	-	Second (metric)
scf	-	Standard cubic feet
sec	-	Second (English)
µm	-	Micrometer
µmA	-	Micrometer, aerodynamic diameter
cmA	-	Centimeter, aerodynamic diameter

Acronyms

ADVACATE	-	Advance Silicate
FGD	-	Flue Gas Desulfurization
SDA	-	Spray dryer absorber
DSI	-	Dry sorbent injector
ESP	-	Electrostatic precipitator
EPRI	-	Electric Power Research Institute
EPA	-	U.S. Environmental Protection Agency
DOE	-	U.S. Department of Energy
LIMB	-	Limestone Injection Multistage Burners
SNRB	-	Slow NOx Reduction Burners
HETP	-	Height Equivalent to Theoretical Plate

Course Description

In this course, you will learn how various wet and dry scrubbers operate and how to evaluate the effectiveness of scrubber designs in reducing particulate and gaseous emissions from industrial sources. Major topics include the following:

- General description of various wet and dry scrubber designs
- Particle collection and absorption theory
- Operation and maintenance problems associated with scrubbers
- Scrubber components
- Use of scrubbers in flue gas desulfurization (FGD)
- Estimating collection efficiency of wet scrubbing systems
- Determining the liquid requirements for gas absorbers
- Sizing plate towers and packed towers (height and diameter)

Objectives

Upon completion of this course, you will be able to do the following:

1. Identify various scrubber designs (both wet and dry) and briefly describe their operation
2. Briefly describe the mechanisms for particle collection and gas absorption in a scrubber
3. List three key design parameters affecting particle and gaseous pollutant removal
4. Identify which scrubbers are used mainly for particle collection and which are used mainly for gaseous pollutant removal
5. Describe typical operation and maintenance problems associated with various wet and dry scrubbers
6. Briefly describe four FGD systems used for removing sulfur dioxide emissions from boilers
7. Use estimating techniques and typical "rules of thumb" to evaluate scrubber plan designs for collection efficiency, adequate liquid flow rates, and proper sizing

Audience

This course is intended primarily for air permit reviewers and air quality inspectors employed by state and local agencies. The course also provides useful training for technical personnel in private industry who prepare permit applications and are responsible for operating scrubbers in compliance with air quality regulations.

Course Length and CEUs

This course will take approximately 40 hours to complete. The number of Continuing Education Units (CEUs) awarded with successful completion of the course is 4.

Suggested Prerequisites

Prior to taking this course, completion of the following U.S. EPA APTI courses or the equivalent of one year's experience in the air pollution control field is recommended:

SI:422 *Air Pollution Control Orientation Course* or 452 *Principles and Practices of Air Pollution Control*

SI:100 *Mathematics Review for Air Pollution Control*

You should also be able to use a calculator with various math functions.

Required Materials

- Self-Instructional Manual, *Scrubber Systems Operation Review*
- Final examination
- Calculator

Supplemental Materials

- Video titled, *Venturi Scrubbers: Operating Principles and Components*

Taking the Course

Proceed sequentially through the manual until you have completed Lesson 11. The review exercises located at the end of every lesson test your mastery of the objectives covered in that lesson. The review exercises are designed so that you can either complete them as you finish a section of the lesson material or wait until you have completed the entire lesson. The review exercises in Lessons 10 and 11 give you the opportunity to test your abilities in solving problems similar to the example problems presented in those lessons. The video, *Venturi Scrubbers: Operating Principles and Components* is optional. If you acquire a copy, view it at the end of Lesson 3.

Each lesson contains the following:

Learning goal and objectives

Text material

Review exercises and exercise answers

For each lesson, follow these steps:

1. Do the assigned reading and view the assigned videotapes.
2. Complete the review exercise.
3. Check your answers against the key.
4. Review the instruction for any questions that you answered incorrectly.

Completing the Course

A final examination accompanies this book (provided in a separate envelope). Take the final exam after you have finished the course. The exam is a *closed book* exam. Do not use your notes or books.

The final examination counts as 100% of your grade. To receive your certificate of completion and 4 Continuing Education Units (CEUs), you must score 70 or above on the exam. Follow these procedures:

1. Arrange for someone to be your test supervisor and give him/her the envelope.
2. Complete the final exam under the supervision of your test supervisor according to the test directions.
3. After you have finished the exam, ask the test supervisor to sign a statement on the answer sheet certifying that you took the exam in accordance with the specified test directions.

4. Have your test supervisor mail the exam and answer sheet to the appropriate registrar below:

   Registrar - Private Sector

   NCSU Environmental Programs
   Box 7902
   Raleigh, NC 27695 - 7902
   Phone: (919) 515-5875
   Fax: (919) 515-4386

   or

   Registrar - EPA/State Agency

   U.S. Environmental Protection Agency
   MD-17
   Research Triangle Park, NC 27711
   Phone: (919) 541-2497
   Fax: (919) 541-5598

   Your exam and grade results will be mailed to you.

Lesson 1

Introduction to Scrubbing Systems

Goal

To familiarize you with scrubbers, the reasons they are used for emission reduction, and the review process for evaluating scrubber design.

Objectives

At the end of this lesson, you will be able to do the following:

1. Briefly describe the purpose and process of wet and dry scrubbing
2. List four advantages and disadvantages of using wet scrubbers to collect particles and gases compared to using other air pollution control devices
3. Describe at least five components of a wet scrubbing system
4. Describe the major differences between wet and dry scrubbers
5. Identify two different types of dry scrubbers

Introduction

Scrubber systems are a diverse group of air pollution control devices that can be used to remove particles and/or gases from industrial exhaust streams. Traditionally, scrubbers have referred to pollution control devices that used liquid to "scrub" unwanted pollutants from a gas stream. Recently, the term *scrubber* is also used to describe systems that inject a dry reagent or slurry into a dirty exhaust stream to "scrub out" acid gases. Scrubbers are one of the primary devices that control gaseous emissions, especially acid gases.

Wet Scrubbers

Wet scrubber is a term used to describe a variety of devices that use liquid to remove pollutants. In a wet scrubber, the dirty gas stream is brought into contact with the scrubbing liquid by spraying it with the liquid, by forcing it through a pool of liquid, or by some other contact method.

Of course the design of any air pollution control device (wet scrubbers are no exception) depends on the industrial process conditions and the nature of the air pollutants involved.

Exhaust gas characteristics and dust properties, if particles are present, are of primary importance. Scrubbers can be designed to collect particulates and/or gaseous pollutants. Wet scrubbers remove particles by *capturing* them in liquid droplets. Wet scrubbers remove pollutant gases by *dissolving* or *absorbing* them into the liquid. Any droplets that are in the flue gas must then be separated from the clean exhaust stream by means of another device referred to as a **mist eliminator** or **entrainment separator** (these terms are interchangeable). Also, the resultant scrubbing liquid must be treated prior to any ultimate discharge or reused in the plant.

There are numerous configurations of scrubbers and scrubbing systems—all designed to provide good contact between the liquid and dirty gas stream. Figures 1-1 and 1-2 show two examples of wet scrubber designs, including their mist eliminators. Figure 1-1 is a venturi scrubber design, which is discussed in greater detail in Lesson 3. The mist eliminator for a venturi scrubber is often a separate device called a cyclonic separator. Figure 1-2 has a tower design where the mist eliminator is built into the top of the structure. Various tower designs are covered in lessons 3, 4, 5, and 6. Entrainment separators and mist eliminators are covered in more detail in Lesson 8.

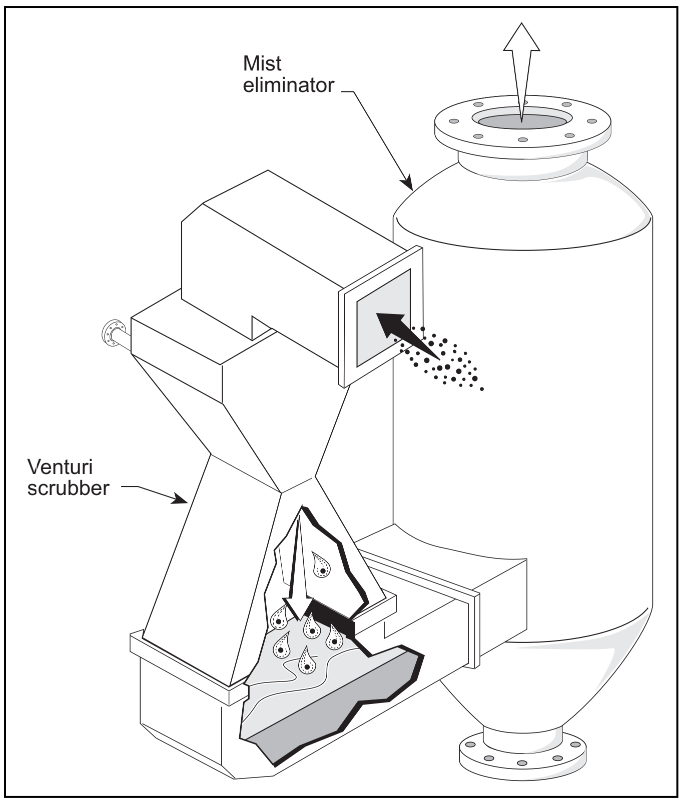

Figure 1-1. An example of a venturi scrubber design

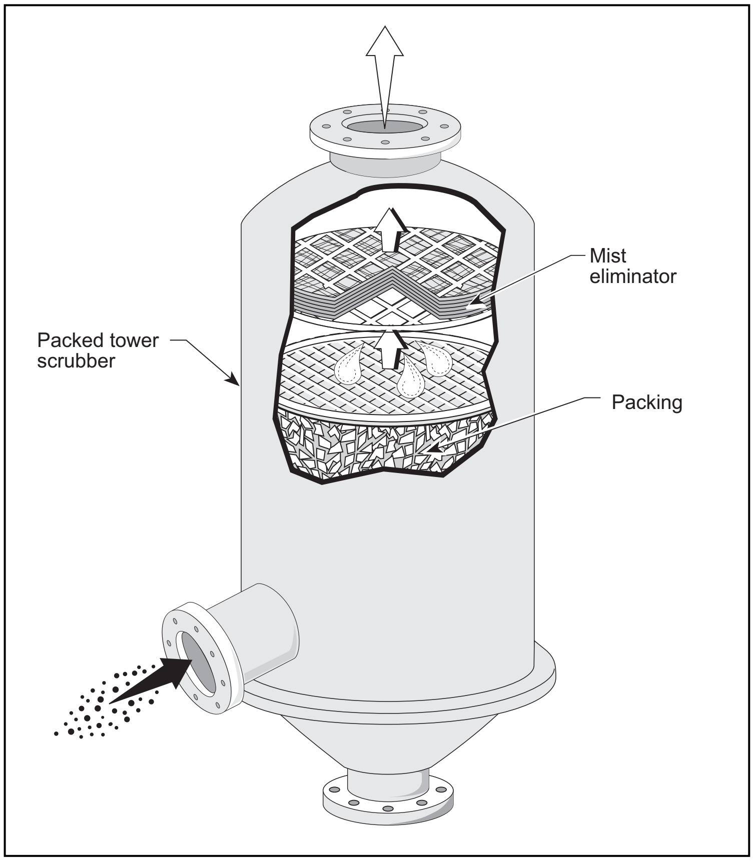

Figure 1-2. An example of a tower scrubber design

A wet scrubber's ability to collect small sized particulates is often directly proportional to the power input into the scrubber. Low energy devices such as spray towers are used to collect particulate matter larger than 5 micrometers. To obtain high efficiency removal of 1 micrometer (or less) particles generally requires high energy devices such as venturis or augmented devices such as condensation scrubbers. Additionally, a properly designed and operated entrainment separator/mist eliminator is important to achieve high removal efficiencies: the greater the number of liquid droplets that are not captured by the mist eliminator the higher the potential emission levels.

Wet scrubbers that remove gaseous pollutants are referred to as **absorbers**. Good gas-to-liquid contact is essential to obtain high removal efficiencies in absorbers. A number of wet scrubber designs are used to remove gaseous pollutants, with the **packed tower** and the **plate tower** being the most common.

If the exhaust stream contains both particles and gases, wet scrubbers are generally the only single air pollution control device that can remove both types of pollutants. Wet scrubbers can achieve high removal efficiencies for either particles or gases and, in some instances, can achieve a high removal efficiency for both pollutants in the same system. However, in many cases, the best operating conditions for particle collection are the poorest for gas removal. In general, obtaining high simultaneous gas and particle removal efficiencies requires that one of them be easily collected (i.e., that the gases are very soluble in the liquid or that the particles are large and readily captured).

For particulate control, wet scrubbers (also referred to as wet collectors) are evaluated against fabric filters and electrostatic precipitators (ESPs). Some advantages of wet scrubbers over these devices are as follows:

- Wet scrubbers have the ability to handle high temperatures and moisture.
- In wet scrubbers, flue gases are cooled, resulting in smaller overall size of equipment.
- Wet scrubbers can remove both gases and particles.
- Wet scrubbers can neutralize corrosive gases.

Some disadvantages of wet scrubbers include corrosion, the need for mist removal to obtain high efficiencies, the need for treatment or reuse of spent liquid, and reduced plume buoyancy. Table 1-1 summarizes these advantages and disadvantages. Wet scrubbers have been used in a variety of industries such as acid plants, fertilizer plants, steel mills, asphalt plants, and large power plants.

Table 1-1. Relative advantages and disadvantages of wet scrubbers compared to other control devices

Advantages	Disadvantages
Small space requirements Scrubbers reduce the temperature and volume of the unsaturated exhaust stream. Therefore, vessel sizes, including fans and ducts downstream, are smaller than those of other control devices. Smaller sizes result in lower capital costs and more flexibility in site location of the scrubber.	**Corrosion problems** Water and dissolved pollutants can form highly corrosive acid solutions. Proper construction materials are very important. Also, wet-dry interface areas can result in corrosion.
No secondary dust sources Once particles are collected, they cannot escape from hoppers or during transport.	**High power requirements** High collection efficiencies for particles are attainable only at high pressure drops, resulting in high operating costs.
Handles high-temperature, high-humidity gas streams No temperature limits or condensation problems can occur as in baghouses or ESPs.	**Water-disposal problems** Settling ponds or sludge clarifiers may be needed to meet waste-water regulations.
Minimal fire and explosion hazards Various dry dusts are flammable. Using water eliminates the possibility of explosions.	**Difficult product recovery** Dewatering and drying of scrubber sludge make recovery of any dust for reuse very expensive and difficult.
Ability to collect both gases and particles	**Meteorological problems** The saturated exhaust gases can produce a wet, visible steam plume. Fog and precipitation from the plume may cause local meteorological problems.

Wet Scrubber Systems

Wet scrubber systems generally consist of the following components:

- Ductwork and fan system
- A saturation chamber (optional)
- Scrubbing vessel
- Mist eliminator
- Pumping (and possible recycle system)
- Spent scrubbing liquid treatment and/or reuse system
- Exhaust stack

Figure 1-3 illustrates a typical wet scrubbing process. Hot flue gas enters the saturator where gases are cooled and humidified prior to entering the scrubbing area. The saturator removes a small percentage of the particles present in the flue gas. Next, the gas enters the venturi scrubber where approximately half of the gases are removed. By the time the gas exits the venturi, 95% of the particles have been removed. The gas flows through a second scrubber, a packed bed absorber, where the rest of the gases (and particles) are collected. The mist eliminator removes any liquid droplets that may have become entrained in the flue gas. The recirculation pump moves some of the spent scrubbing liquid back to the venturi scrubber where it is recycled and the remainder is sent to a treatment system. Treated scrubbing liquid is recycled back to the saturator and the packed bed absorber. Fans and ductwork move the flue gas stream through the system and eventually out the stack.

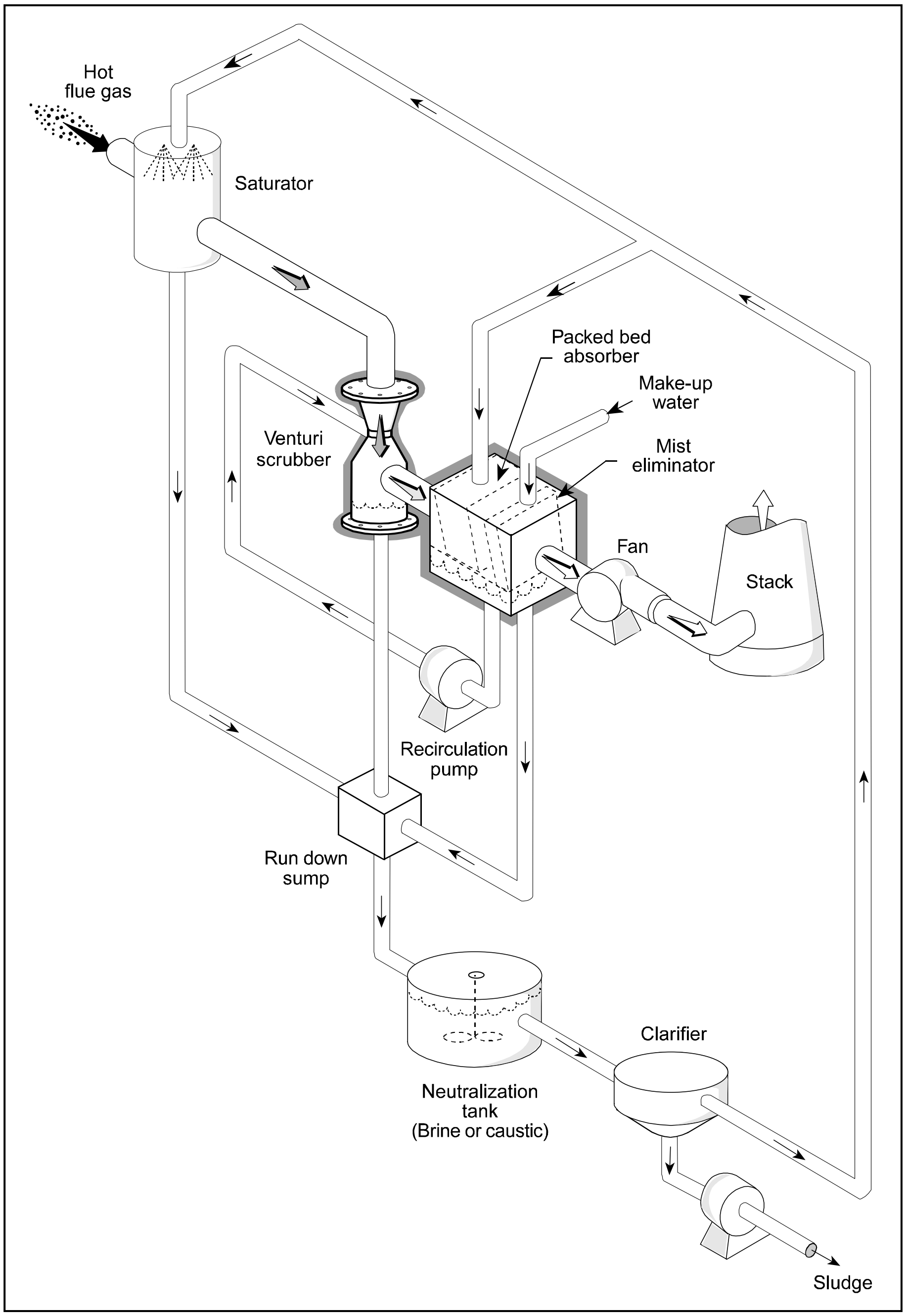

Figure 1-3. An example of a wet scrubbing system

Categorization of Wet Scrubbers

Since wet scrubbers vary greatly in complexity and method of operation, devising categories into which all of them neatly fit is extremely difficult. Scrubbers for particle collection are usually categorized by the gas-side pressure drop of the system. **Gas-side pressure drop** refers to the pressure difference, or pressure drop, that occurs as the exhaust gas is pushed or pulled through the scrubber, disregarding the pressure that would be used for pumping or spraying the liquid into the scrubber. In this manual, the terms *pressure drop* and *gas-side pressure drop* will be used interchangeably. Classification of scrubbers by pressure drop is as follows:

- Low-energy scrubbers have pressure drops of less than 12.7 cm (5 in.) of water.
- Medium-energy scrubbers have pressure drops between 12.7 and 38.1 cm (5 and 15 in.) of water.
- High-energy scrubbers have pressure drops greater than 38.1 cm (15 in.) of water.

However, most scrubbers operate over a wide range of pressure drops, depending on their specific application, thereby making this type of categorization difficult.

Another way to classify wet scrubbers is by their use—to primarily collect either particles or gaseous pollutants. Again, this distinction is not always clear since scrubbers can often be used to remove both types of pollutants.

In this course, wet scrubbers are categorized by the manner in which the gas and liquid phases are brought into contact. Scrubbers are designed to use power, or energy, from the gas stream or the liquid stream, or some other method to bring the pollutant gas stream into contact with the liquid. These categories are given in Table 1-2.

Table 1-2. Categories of wet collectors by energy source used for contact

Wet collector	Energy source used for gas-liquid contact
Gas-phase contacting	Gas stream
Liquid-phase contacting	Liquid stream
Wet film	Liquid and gas streams
Combination	
• Liquid phase and gas phase	Liquid and gas streams
• Mechanically aided	Mechanically driven rotor

Each of the wet collectors listed in Table 1-2 will be discussed in this course. For each design category, the following topics will be discussed: operation, collection efficiency, industrial applications, prominent maintenance problems and, when applicable, primary use.

Dry Scrubbing Systems

A dry or semi-dry scrubbing system, unlike the wet scrubber, does not saturate with moisture the flue gas stream that is being treated. In some cases no moisture is added; while in other designs only the amount of moisture that can be evaporated in the flue gas without condensing is added. Therefore, dry scrubbers do not have a stack steam plume or wastewater handling/disposal requirements. Dry scrubbing systems are used to remove acid gases (such as SO_2 and HCl) primarily from combustion sources. There are a number of dry type scrubbing system designs. However, all consist of two main sections or devices: (1) a device to introduce the acid gas sorbent material into the gas stream and (2) a particulate-matter control device to remove reaction products, excess sorbent material as well as any particulate matter already in the flue gas. Dry scrubbing systems can be categorized as dry sorbent injectors (DSIs) or as spray dryer absorbers (SDAs). Spray dryer absorbers are also called *semi-dry scrubbers* or *spray dryers*. Figures 1-4 and 1-5 illustrate both the DSI and spray dryer processes.

Dry sorbent injection involves the addition of an alkaline material (usually hydrated lime or soda ash) into the gas stream to react with the acid gases. The sorbent can be injected directly into several different locations: (1) the combustion process, (2) the flue gas duct (ahead of the particulate control device), or (3) an open reaction chamber (it one exists). The acid gases react with the alkaline sorbents to form solid salts which are removed in the particulate control device. These simple systems can achieve only limited acid gas (SO_2 and HCl) removal efficiencies.

Higher collection efficiencies can be achieved by increasing the flue gas humidity (i.e., cooling using water spray). These devices have been used on medical waste incinerators and a few municipal waste combustors.

In **spray dryer absorbers**, the flue gases are introduced into an absorbing tower (dryer) where the gases are contacted with a finely atomized alkaline slurry. Acid gases are absorbed by the slurry mixture and react to form solid salts which are removed by the particulate control device. The heat of the flue gas is used to evaporate all the water droplets, leaving a non-saturated flue gas to exit the absorber tower. Spray dryers are capable of achieving high (80+%) acid gas removal efficiencies. These devices have been used on industrial and utility boilers and municipal waste combustors.

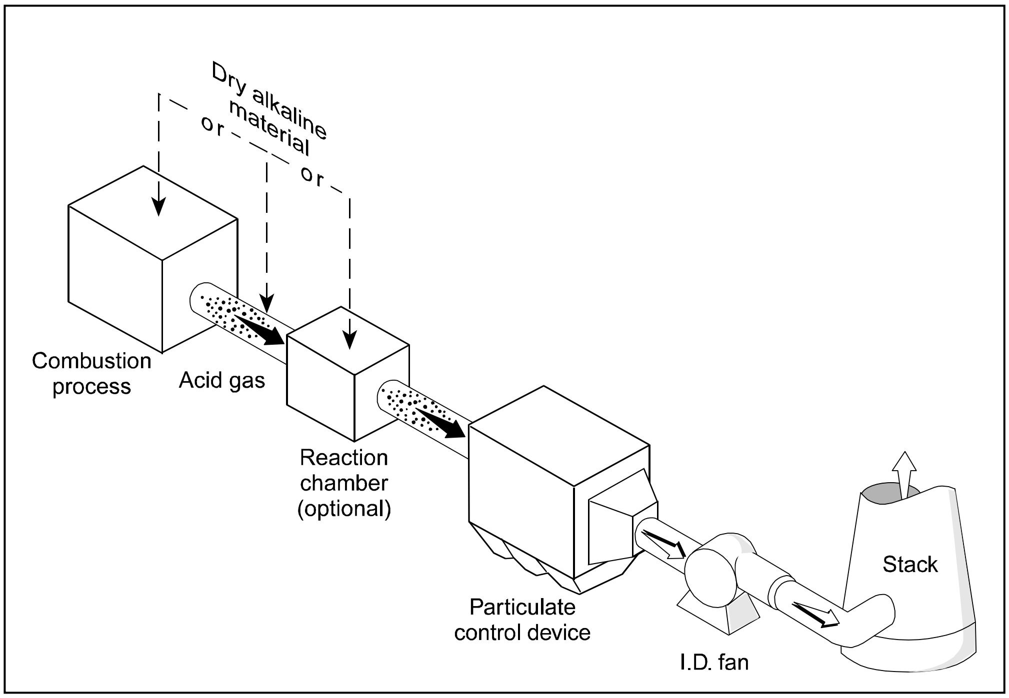

Figure 1-4. Dry sorbent injection scrubber system

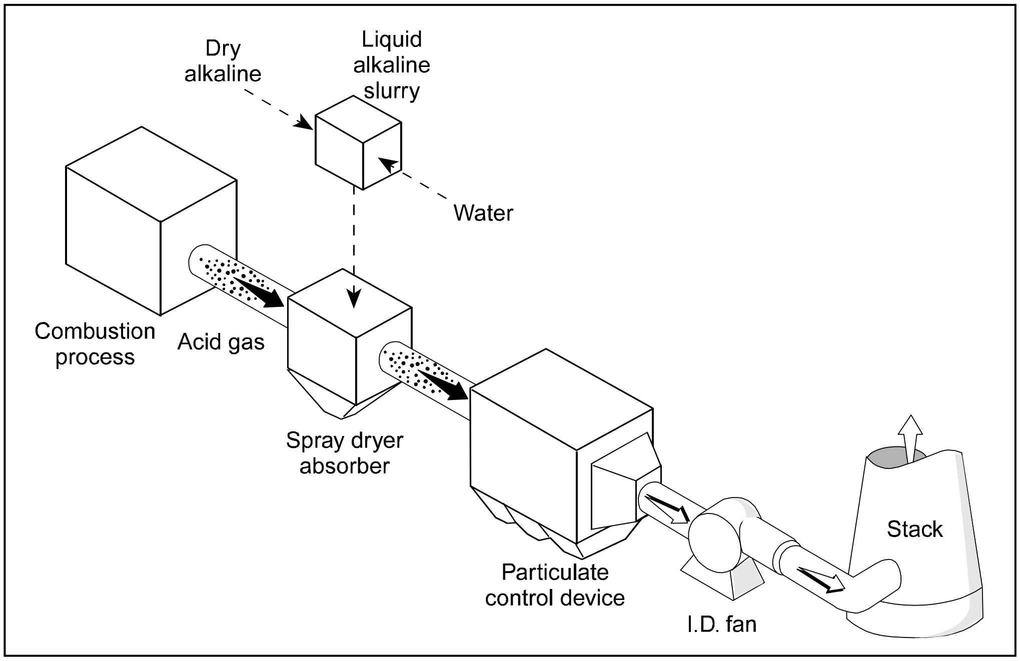

Figure 1-5. Spray dryer absorber system

Design Evaluation

In evaluating a new scrubber design, especially from a regulatory viewpoint, the major issue is whether the proposed design will achieve the required particle and/or gaseous removal levels. There are three basic approaches to evaluating the capability of scrubbing systems: (1) empirical evaluations based on historical data on similar scrubbers, (2) theoretical models based on basic engineering principles and (3) pilot scale test data. Scrubber vendors utilize all three, especially historical data to design their systems. A person reviewing scrubber plans generally will not have access to all necessary data and may be limited to using the theoretical equations. In this workbook, operating information on various scrubbing systems along with basic theoretical models are presented so that a reviewer can utilize both to perform evaluations of scrubbing systems.

The design and operation of these systems are based on the basic laws of physics and general chemical engineering principles. For example, most scrubbers require a certain velocity (or residence time) through the vessel to obtain the required removal efficiency. This parameter is set by the size of the scrubber in relation to the volume of flue gas to be treated. In performing an in-depth evaluation of a scrubbing system there are certain parameters that should be verified such as the velocity, pressure drop or power input, and sorbent or reagent usage rate. For the more popular types of scrubbing systems there are general "rules of thumb" and empirical relationships that can be used to determine if scrubber design and operating parameters are within "normal" ranges. However, because of the variety of scrubber designs and the complex mass and heat balance transfer occurring in a scrubber, there is no one set of *simple* equations that can be used to do an in-depth evaluation of all scrubbing systems. Scrubber vendors utilize past operating and pilot scale data to refine system designs to specific applications.

To evaluate scrubber designs, this document provides both operating information on specific scrubbers and generalized review equations and procedures for common scrubbers. Reviewers can use the operating data to do the following:

- Determine whether the system being evaluated is within normal ranges for similar types of systems
- Make sure common operating problems are being addressed
- Assure that adequate data monitoring devices are specified and that data are being recorded

Utilizing all this information, a reviewer can develop a list of questions to be answered by the vendor/or operator in order to confirm adequate design of the system.

As is the case with any pollution control system, the ultimate proof of system design is in the guarantee and start-up performance test. Vendors will guarantee certain performance (efficiency) parameters, and these guarantee points should be evaluated in an initial review process. The initial stack and performance test will highlight any major design problem. Day-to-day operation will need to be assessed from monitoring instrumentation.

In addition to being useful to persons evaluating a new scrubber design, information presented in this course is also intended to be useful to persons responsible for overseeing the day-to-day operation and/or inspection of a scrubbing system. Evaluation of scrubber system performance begins with developing good *baseline* information on the important operating parameters. Using the information presented in this course on these operating parameters, a person can develop appropriate recordkeeping or checklists to evaluate scrubber operation. Also, example troubleshooting summaries are presented for certain scrubber designs. Regulatory personnel could use these lists as a guide to formulate questions or identify areas to investigate during a routine inspection of a facility. As with the design review, there is no one set of procedures or guidelines that can be used to evaluate operation and maintenance of all scrubber systems. General procedures presented in this course need to be customized to site specific applications.

Summary

Wet scrubbing systems are devices that use a liquid (generally water) to remove particulate and/or gaseous pollutants from a process exhaust gas stream. There are numerous different configurations of wet scrubbers. All designs attempt to provide good liquid-to-pollutant contact in order to obtain high removal (95% plus) efficiencies. Wet scrubbers saturate the gas stream thereby creating a steam plume and resulting wastewater stream that must be treated or reused in the plant. Also, since the gas stream is saturated with liquid, a mist eliminator or entrainment separator is often an integral part of any wet scrubbing system. Mist eliminators (entrainment separators) remove and/or recycle the scrubbing liquid in addition to providing additional pollutant removal.

Dry and semi-dry scrubbing systems are used to remove acid gases from combustion gas streams. These systems utilize a powder sorbent material, either calcium (lime) or sodium based to react with the acid gases in the flue gas and produce a solid salt that must be removed in a particulate control device. In dry systems, also referred to as dry sorbent injection, the dry powder sorbent material is injected directly into the ductwork, or reaction chamber. In a semi-dry (or spray dryer absorber) system, the sorbent material is first mixed with water and then injected into a spray drying vessel where all the liquid is totally evaporated by cooling the gas stream while the sorbent reacts with the acid gases. By cooling the hot combustion gas stream, higher acid gas removal efficiencies are achievable than with simple duct injection.

To evaluate scrubber designs, this manual provides both a generalized review of design equations/procedures and operating information on specific scrubbing systems. Reviewers can use this information to determine if the scrubbing system is operating within normal ranges compared to other similar systems. This will provide the reviewer with a starting point to develop a list of questions aimed at vendors or operators that will aid in evaluating the adequacy of the design.

The next lesson provides an overview of the design features of wet and dry scrubbers that enhance collection of pollutants.

Review Exercise

1. True or False? Both wet and dry scrubbers can be used to remove both gaseous and particulate emissions.
2. Where is the mist eliminator (entrainment separator) located in relation to the scrubber vessel?
   a. The mist eliminator is always separate from the scrubber vessel.
   b. The mist eliminator is always built into the same structure as the scrubber vessel.
   c. Depending on the scrubber design, the mist eliminator can either be a separate structure from the scrubber vessel or built into it.
3. A wet scrubber's ability to remove very small sized particles is often related to the:
   a. Size of the system
   b. Flow pattern
   c. Power input
   d. Sorbent
4. In general, high removal rates for both particles and gases in the same scrubber are obtained by:
   a. The use of large amounts of water
   b. Having gases that are highly soluble and/or particles that are relatively large
   c. The use of extremely high pressure drops
   d. A reagent added to the water
5. For particulate control, wet scrubbers are evaluated against two other types of control devices: ____________________ ____________________ and ____________________ ____________________.
6. True or False? Wet scrubbers used for particulate control have the advantage of being able to handle high-temperature and high-moisture gas streams.
7. Wet scrubbers are ____________________ than fabric filters or electrostatic precipitators used for the same application.
   a. Larger
   b. Smaller
   c. Less noisy
   d. b and c, only
8. Compared to fabric filters or electrostatic precipitators, wet scrubbers have the following disadvantage(s):
   a. Smaller equipment size
   b. Reduced plume buoyancy
   c. Need for treatment or reuse of spent scrubbing liquid
   d. b and c, only

9. Dry scrubbing systems consist of two main sections:

   a. A quench tower and mist eliminator
   b. A device to introduce the sorbent and a particulate control device
   c. A venturi and a packed scrubber
   d. A liquid and a dry section

10. The two types of dry scrubbing systems are:
    _____________________ _____________________ _____________________ and
    _____________________ _____________________ _____________________.

11. A spray dryer uses a finely atomized _____________________ of alkaline sorbent to remove acid gases.

    a. Liquid slurry
    b. Dry slurry
    c. Gas stream
    d. Any of the above

Review Exercise Answers

1. **False**
   Only wet scrubbers can remove both gaseous and particulate emissions.
2. **c. Depending on the scrubber design, the mist eliminator can either be a separate structure from the scrubber vessel or built into it.**
   The location of the mist eliminator (entrainment separator) in relation to the scrubber vessel depends on the scrubber design. The entrainment separator for a venturi scrubber is often a separate device (cyclonic separator). Scrubbers with tower designs have the mist eliminator built into the top of the structure.
3. **c. Power input**
   A wet scrubber's ability to remove very small sized particles is often related to the power input.
4. **b. Having gases that are highly soluble and/or particles that are relatively large**
   In general, high removal rates for both particles and gases in the same scrubber are obtained by having gases that are highly soluble and/or particles that are relatively large.
5. **Fabric filters**
   Electrostatic precipitators
   For particulate control, wet scrubbers are evaluated against two other types of control devices: fabric filters and electrostatic precipitators.
6. **True**
   Wet scrubbers used for particulate control have the advantage of being able to handle high-temperature and high-moisture gas streams.
7. **b. Smaller**
   Wet scrubbers are smaller in size than fabric filters or electrostatic precipitators used for the same application.
8. **d. b and c, only**
   When compared to fabric filters or electrostatic precipitators, wet scrubbers have the following disadvantages:
   - Reduced plume buoyancy
   - The need for treatment or reuse of spent scrubbing liquid
9. **b. A device to introduce the sorbent and a particulate control device**
   Dry scrubbing systems consist of two main sections: a device to introduce the sorbent and a particulate control device.
10. **Dry sorbent injection**
    Spray dryer absorber
    The two types of dry scrubbing systems are dry sorbent injection and spray dryer absorber.
11. **a. Liquid slurry**
    A spray dryer uses a finely atomized liquid slurry of alkaline sorbent to remove acid gases.

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